Evaluation and Quantification of Randomness in Free-fall Trajectories of Instrumented Cylinders

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Abstract- **As part of a field experiment designed to contribute to the Navy's effort to improve its capability to model and predict depth of burial of anti-sip mines in mud seafloors, the trajectory, velocity and orientation of a 1,100-kg cylinder were observed during 21 free-fall trials in a field setting. Extreme values and distribution of linear and angular velocity components as well as orientation throughout the water column and, in particular, on impact with the sediment are described. The findings indicate that a critical depth (of about 4 m, for the cylinder configuration tested) appears to exist beyond which the influence of the release conditions is insignificant. All the different nose shapes tested resulted in similar mean values of velocities and orientations. Cylinders with chamfered noses appear to possess the highest variability in these parameters, complicating the mine burial modeling effort. Periodic nature in the variation of several parameters was observed and its changes with cylinder geometry presented. Overall implications on the impact burial prediction analysis of heavy, cylindrical shapes are discussed.**

I. INTRODUCTION

The main objective of this study is to collect, systematically analyze, and quantify the experimental data on the complex three-dimensional behavior of an instrumented cylinder during freefall. This information is relevant to the implementation of the mine burial procedures, calculating the amount of burial of a potential mine in the seafloor marine sediments, and depends on our knowledge of the two main categories of data. One consists of the accurate description of the characteristics of the bottom sediments, pertaining to the high strain and high strain rate deformation. This knowledge also needs to reflect the natural variability of these parameters in both spatial and temporal domains. Information on the linear and angular velocities and orientation of the falling mine at the point of impact on the sediment floor represents the second class of the input information, required for the penetration burial prediction.

Behavior of cylindrical bodies during free-fall has been modeled in the past [1] and [2]. Further developments are underway, involving improved and more realistic approaches, e.g. [3]. Accurate numerical modeling depends in large on the ability to describe the complex three-dimensional dynamic behavior of a mine and requires proper accounting for all the forces acting on the falling cylinder. Under ideal conditions, the water column is usually represented as a semi-infinite space with isotropic and constant properties. These properties include temperature, salinity, density, and other parameters. Under these conditions, it has been shown that an idealized cylindrical mine body, free-falling through the water, could reach a number of stable or quasi-stable motion patterns [1]. Depending on the geometry and the distribution of mass, a range of trajectories can be expected. Several distinct patterns have been experimentally observed and were identified as straight, spiral, flip, flat, seesaw. A single trajectory may consist of a single pattern or any number and any combination of these motions. Each one of these patterns appears to be stable and if the mine enters a particular pattern, it will remain in this pattern until a sufficient disturbance is applied to the moving body.

In reality, the disturbances are abundant. Heterogeneous state of the ocean, currents, changing with depth and time, variations of the water density and salinity are among the most important factors. In order to reproduce a specific experimental trajectory one will need to have precise knowledge of these factors at the time of deployment. Since this information is often difficult to quantify reliably, and therefore be able to model accurately, it appears that a more general approach is needed, where these influences, which result in various motion patterns, can be described statistically, with sufficiently significant accuracy. This type of empirical model could provide sufficiently accurate predictions of the

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14. ABSTRACT

The trajectory, velocity and orientation of a 1,100-kg cylinder during free-fall in seawater is described and discussed. This work contributes to the Navy's effort to improve its capability to predict depth of burial of anti-ship mines in mud seafloors. The chaotic nature of trajectories for 21 trials is quantified and evaluated to describe the range of velocities and orientations to be encountered. Extreme values and distribution of linear and angular velocity components as well as orientation throughout the water column and, in particular, on impact with the sediment are described. The findings indicate that -a critical depth (of about 4 m, for the cylinder configuration tested) appears to exist beyond which the influence of the release conditions is insignificant. All the different nose shapes tested resulted in similar mean values of velocities and orientations. Cylinders with chamfered noses appear to possess the highest variability in these parameters, complicating the mine burial modeling effort. Periodic nature in the variation of several parameters was observed and its changes with cylinder geometry presented. Overall implications on the impact burial prediction analysis of heavy, cylindrical shapes are discussed.

15. SUBJECT TERMS

trajectory, velocity, cylinder, free-fall, mud seafloors

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freefall of mines through the water and penetration burial into the seafloor.

For the first time, a full scale instrumented cylinder has been released in a realistic field setting. The instrument data is used to characterize the statistics of the dynamic behavior exhibited by this cylinder. In the next section (Experimental Setup) we describe the instrumented cylinder and its deployment. Then, we present the statistical characterization of the observational results (Results). These results suggest that after a short initial period, the freefalling cylinders reach a quasi-stable state, with oscillations about a mean, and we discuss the implications for mine burial prediction (Discussion). Our findings are summarized in the conclusion section.

It is important to underline that the overall goal is to be able to predict the amount of burial of mine bodies in the seafloor sediments. Thus, the accurate description of the conditions of the mine at the point of initial contact with the sediment, in the statistical sense, is crucial to the ability to exercise the sediment component of the impact burial prediction model.

II. EXPERIMENTAL SETUP, EQUIPMENT AND PROCEDURES

Instrumented cylinder and data acquisition

The instrumented cylinder measures 0.53 m in diameter and 2.40 m long, yielding a length to diameter ratio of 4.5. Its weight in air is approximately 10 kN (2250 lb) and its weight in water (seawater) is about 4.9 kN. Most bottom mines of the type considered here are slightly nose heavy, and so the instrumented cylinder designed for this study had the distance between the center of mass (CM) and the center of volume (CV) of 0.104 m, with the CM located forward of the CV. Three different and interchangeable nose shapes were manufactured: blunt, hemispherical, and chamfered, again representing a variety of operational mines. Fig. 1 depicts the instrumented cylindrical shape, strapped to a cradle and with the blunt nose mounted.

The internal instrumentation, placed in the sealed container inside the cylinder, included a set of accelerometers measuring along three orthogonal axes. These accelerometers had three different ranges: 2.5g, 4g, and 10g. Additionally, a tri-axial fiber-optic gyro (FOG) measured the angular rotation rate about three orthogonal axes, collinear with the axes of the accelerometer. A tri-axial magnetometer was also placed inside the instrumentation chamber. Interpretation of its measurements, however, was not implemented due to the difficulties in calibration. The internal instrumentation also included a power source, a signal acquisition and conditioning unit, and a fast

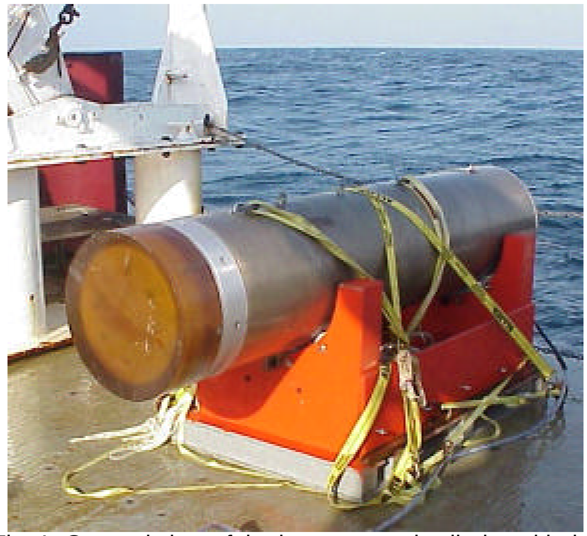

Fig. 1. General view of the instrumented cylinder with the blunt nose attached

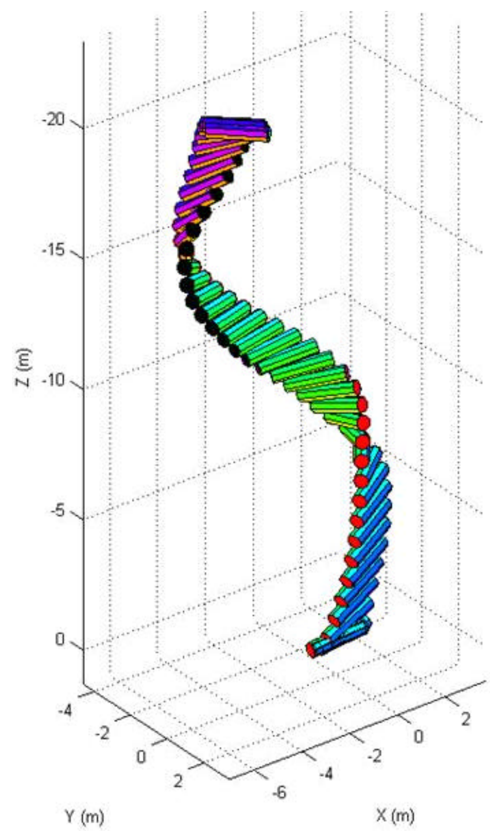

Fig. 2. A typical calculated trajectory of the instrumented cylinder in free-fall

access memory storage device.

An upgraded and expanded version of the data processing software, originally designed by [4], was developed. The raw device data, which included variations of the components of local (cylinder's coordinate system) accelerations and angular rotation rates with time was analyzed. First, the transformation was performed from the local (cylinder) coordinate system to the fixed global system, using the Euler aerospace rotation sequence. The effects of gravity were then removed and the resulting values of accelerations and angular rotation rates were integrated to obtain a set of global (in addition to local) velocities, displacements, and angular changes as functions of elapsed time. Processing from its initial state, with the cylinder suspended from the ship's winch, forward proved somewhat ambiguous and was replaced with the reversed integration from the cylinder's final position at rest, embedded in the sediment, backwards. The advantage of this approach was in the fact that the conditions at rest are easier and more accurately defined than those at the time of release. Comparisons between the forward and reverse integration schemes showed only minor errors in the overall calculated displacements, accumulated over the entire trajectory.

The data post-processing routines resulted in a set of data that allows analysis of many individual components of the process of free fall and penetration into the sediment. Fig. 2 represents an example of a typical visualization of the calculated trajectory of the cylinder during free fall. Accurate and detailed analysis of various components of acceleration also allowed for estimating the initial point of contact of the cylinder with the sediment floor. This point was characterized by a sharp spike in one or more components of the acceleration. The sensitivity of the instruments and the high rate of data acquisition allowed for a relatively accurate determination of this instant in time. This determination was important for separating the two phases of the free-fall: in-water and in-sediment.

Testing procedures

The data reported in this study was obtained during two cruises. These cruises included the January 2002 cruise on board R/V Pelican, in the vicinity of Cocodrie, LA and the May 2002 cruise on board R/V Gyre, in the vicinity of Corpus Christi, TX.

Each of the two trips included a series of drops with varying cylinder nose configurations and initial conditions. Only one nose configuration was used during the Cocodrie trip, while the cylinder with all three noses was tested during the Corpus Christi trip. Release medium was also varied with some of the cylinder deployments performed from the air, usually only a small height above the water surface, and some others released from the fully submerged position of just below the water surface. Additionally, the initial inclination (pitch) was changed by using different strapping. Two configurations were tested: horizontal and at 45 degrees nose down. Table 1 summarizes this information, showing the test name designations, and the release conditions. Test numbers, referred to hereafter, follow the sequential numbering order, given in the first column of the table.

The testing sequence proceeded according to

Table 1. Cylinder configurations and initial conditions

#	Test name	Nose shape	Release medium	Height above water, m	Pitch at release, deg
Corpus Christi, TX, May 2002					
1	G06md02	hemi	water	-0.5	horiz
2	G06md03	blunt	water	-0.6	horiz
3	G06md04	blunt	water	-1.5	45
4	G06md05	blunt	air	0.5	horiz
5	G06md06	blunt	water	-0.8	horiz
6	G06md07	blunt	water	-0.8	horiz
7	G06md08	chamf	water	-0.6	horiz
8	G06md09	chamf	water	-0.8	horiz
9	G06md10	chamf	water	-0.6	horiz
10	G06md11	chamf	water	-0.6	horiz
Cocdrie, LA, January 2002					
11	P02md01	hemi	water	-0.5	horiz
12	P02md02	hemi	water	-0.5	horiz
13	P02md03	hemi	water	-0.5	45
14	P02md04	hemi	air	1	45
15	P02md05	hemi	air	0.5	45
16	P02md06	hemi	air	1	horiz
17	P02md07	hemi	air	0.2	horiz
18	P02md08	hemi	water	-0.5	horiz
19	P02md09	hemi	water	-0.5	45
20	P02md10	hemi	water	-0.5	45
21	P02md11	hemi	air	0.2	45

Notes: Pitch of 0 deg: long axis horizontal
Positive angles are nose down
Chamfered noses – released with chamf-up

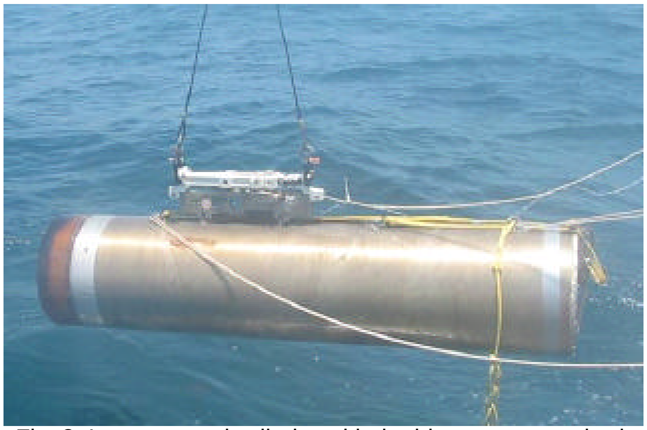

Fig. 3. Instrumented cylinder with the blunt nose attached, before an air release

the following order. First the internal instrumentation of the cylinder, resting in its cradle was initialized. The cylinder was then suspended by either the harness or from the bomb release (as shown in Fig. 3), brought to the desired elevation above or below the water surface and released. A ¼" line was attached to the cylinder and trailed it to the bottom. This line was necessary for the subsequent location and recovery of the cylinder due to almost zero visibility encountered in both deployment areas. The divers then followed this line to the cylinder, located it on the bottom and recorded its final orientation, including the resting angle, and the elevation above the mudline. Additionally, cylinder heading was recorded by the divers using a small compass with storage memory.

In order to confirm the calculated trajectory of the cylinder, including the lateral travel from the point of release to its resting position on the seafloor, a small tethered metal weight ("stake") was also released just prior to the cylinder deployment. The divers then located the stake on the bottom and measured the distance from the stake to the cylinder and the compass heading of this direction to produce a complete set of data that allowed for the computation of the overall lateral travel of the cylinder. The ambient current profile was also measured using ADCP. Analysis of this data showed only minor lateral flows that were considered too small to influence the trajectory of the massive cylinder to any significant degree. Comparison of the diver measured and instrumentation processed data showed good agreement in all those deployments where reliable diver measurements were available. Some equipment difficulties prevented the divers from measuring accurately the headings and the inclinations of the cylinder in some drops.

III. EXPERIMENTAL RESULTS: BEHAVIOR IN THE WATER COLUMN

General

The set of data collected during the two cruises reported herein allows for detailed evaluation of the complex dynamic mechanism of a free-falling cylinder. As evidenced from Fig. 2, and other calculated trajectories, the motions of the cylinder are highly three-dimensional. The corresponding cylinder state, at the point of contact with the sediment, may be described by 9 variables, including three components of velocity, three orientation angles, and three angular rotation rates. The dimensionality of the system can be reduced by considering the symmetries of the problem: axisymmetric body impacting the half-space. In this case, the number of variables reduces to 6: three velocity components, pitch, and two angular rotation rates. Further reductions are possible (keeping only 4 variables), if the impact of the cylinder on the bottom is considered using a two-dimensional model. Here, only two velocity components are of interest, vertical and horizontal, as well as one inclination angle (pitch), and one angular rotation rate. This approach is typical of mine burial prediction models. Since one of the goals of this investigation is to provide an input for the existing mine burial prediction software, which is two dimensional, the results presented herein will address primarily those degrees of freedom of the moving cylinder, that are required for implementing this software. The following components of the cylinder motion are thus of primary interest: vertical velocity, horizontal velocity in the plane of the cylinder, angular rotation rate (in the plane of the cylinder), and the pitch. The "plane of the cylinder" is referred to the plane formed by the cylinder's main axis and the vertical.

The average depths, encountered at the two testing locations were approximately 15 m at Cocodrie, LA and about 20 m off the coast of Corpus Christi, TX. Calibration and testing of any mine burial predictive algorithm would require knowledge of the conditions at impact with the sediment. The data available from the two cruises, however, represents not only the information necessary to drive the predictive software at the two actual depths recorded but also everywhere else, from the point of release and until that maximum depth. The results of the experimental drops would be valid if the sea bottom was encountered at any depth within this interval.

Vertical velocity variations

The vertical component of velocity (V_Z) at impact with the sediment is one of several important factors controlling the final burial depth of a mine. The variation of V_Z with elapsed time is presented in Fig. 4. Part (a) of the figure depicts the entire series of drops from both test locations and includes the overall average with standard deviation. It is evident that the values of the vertical velocity are not necessarily precisely zero at the time of release due to the ship's motion. Sea conditions during the Corpus Christi cruise were significantly more disruptive than those at Cocodrie. This resulted in these initial values of velocity deviating from zero on average more than those from the Cocodrie cruise. Parts (b), (c), and (d) of Fig. 4 show the same data grouped according to the nose geometry, separating between the hemispherical, blunt, and chamfered nose shapes. Solid lines, with data points as circles represent the trajectory of the cylinder from the point of release till the initial contact with the sediment. The solid lines only (with no symbols), that continue from that point on, represent the subsequent motion of the cylinder as it is penetrating into the sediment. This portion of the trajectory is excluded from the analysis herein.

The initial portion of the velocity is steeper for those drops released from air, as is evident in all the diagrams of Fig. 4, with the exception of the

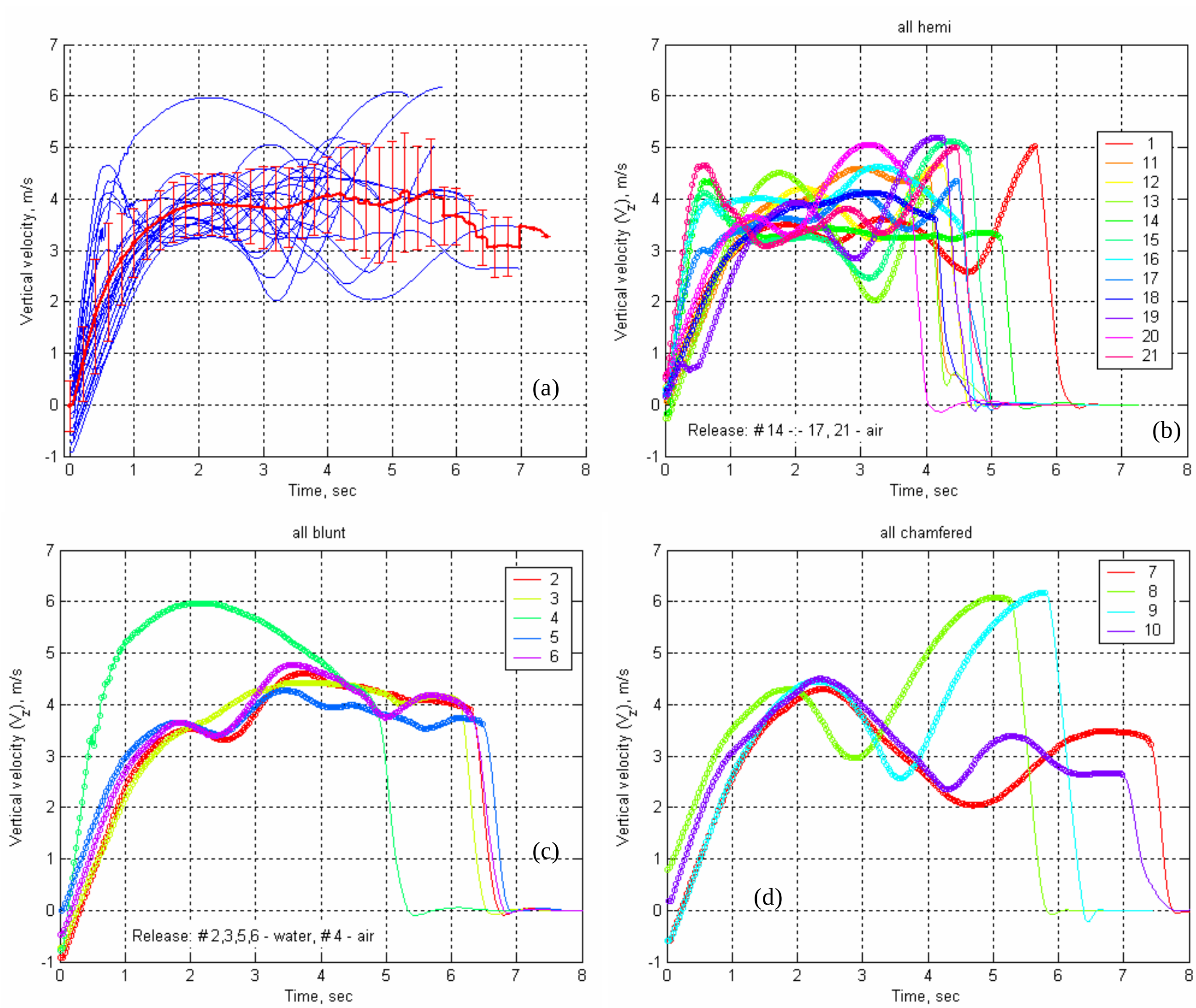

Fig. 4. Vertical velocity versus time for all drops (a), drops with only hemispherical (b), blunt (c), and chamfered noses (d)

chamfered nose, for which no such drops were performed. Drop number 4 in part (c) of the figure, is clearly located away from the rest of the curves and represents the only air drop in this group. It appears that cylinders, during the air drops, acquire the air bubble envelope that changes the behavior of the cylinder for a limited time, until this envelope dissipates. This phenomenon will be further discussed later.

Part (d) of Fig. 4 shows two slightly different patterns repeated in two drops each. Combined with effect of the pitch (discussed below), this effect appears to be the result of the rapid reorientation of the cylinder during free fall due to the chamfered nose that serves as a guiding plane. This promotes more abrupt changes in the orientation, placing the falling cylinder broadside to the vertical direction, which slows it down, or reorienting it vertically, which quickly accelerates it again. These oscillating motions appear to be more extreme than in other nose configurations.

Fig. 5 shows a cumulative histogram of the vertical velocity distribution in all drops performed. The frequency of occurrence of a certain value is normalized by the total count number. The sampled frequency was 0.002 sec. This distribution represents all values registered throughout the drop, from release and until contact with the sediment. As could also be noticed in Fig. 4(a), the dispersion of values is not very high.

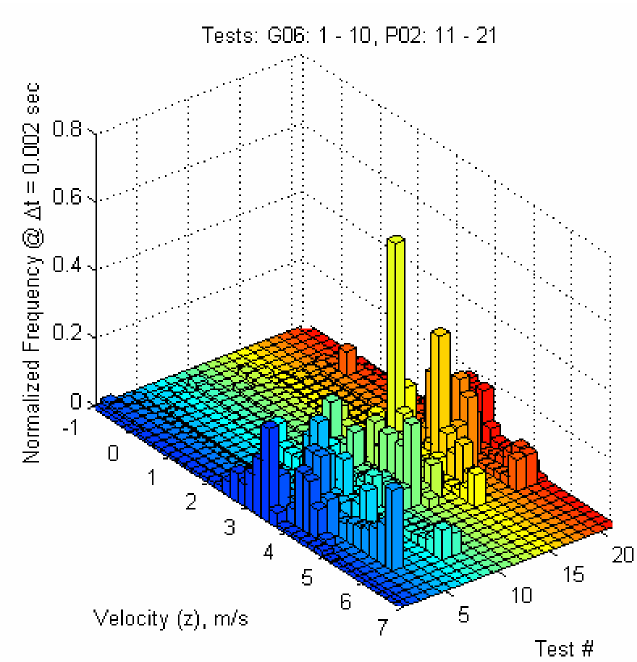

Fig. 5. Normalized frequency of the velocity (vertical component) in all drops

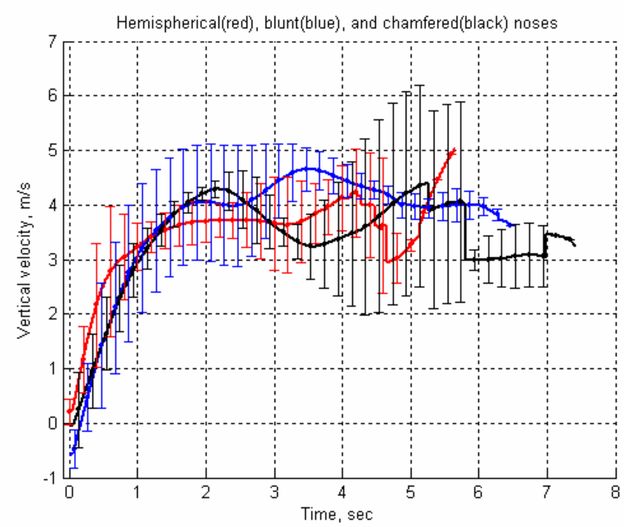

Fig. 6. Average vertical velocity in drops with three different nose types: hemispherical, blunt, and chamfered

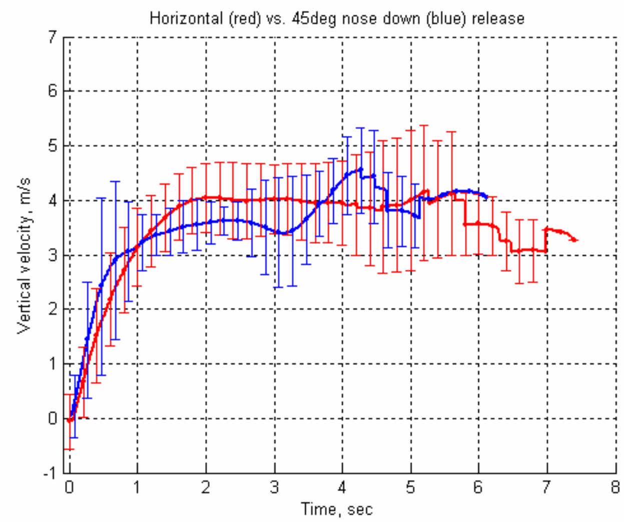

Fig. 7. Average velocity in drops with release pitch at horizontal and 45 deg nose down

In the following two figures, a comparison is performed to find whether a significant difference in vertical velocity distributions exists depending on the particular nose configuration (Fig. 6) and particular release inclination (Fig. 7). Fig. 6 shows vertical velocity distributions for three different nose configurations and demonstrates that all three averages are located very close together, with no significant variations in the distribution of the standard deviations. Thus, the nose type only weakly affects the mean velocity, but appears to have a significant effect on the variation of velocities. The chamfered nose resulted in the largest variability, whereas the blunt and the hemispherical noses both yielded variability that is similar and smaller that that of the chamfered nose. Fig. 7 presents a similar comparison of two initial orientations for all the drops conducted.

Again, no significant difference appears to be present. It has to be noted, that insufficient data is available to analyze the differences between each one of the groups, with only one parameter varied (e.g. nose configuration) and all other parameters fixed, i.e. release medium and release orientation. Additional testing is needed.

Variations in pitch, lateral velocity, and angular rotation rate

Fig. 8 presents the variations in the cylinder pitch, with respect to horizontal, versus time. Part (a) displays results for all the drops performed, together with two averages, calculated individually for the two different initial release inclinations. Parts (b), (c), and (d) represent, individually, the hemispherical, blunt, and chamfered nose configurations, respectively. The initial parts of the curves are grouped about the two initial target inclination values: horizontal (0 deg) and 45 deg (nose down). As was the case with the initial values of the vertical velocity, the initial pitch deviated from its desired values due to the ship's motions and the cylinder added lateral motions, pivoting about the center of the winch hook.

Fig. 9 shows the two averages together with the individual standard deviations. Observation of these figures suggests that the difference between the initial inclinations was practically erased after about 1 sec from release, which represents the average depth of about 1.8 m. From this point on, both groups of curves appear to behave similarly, albeit with very high deviations from the average. An evaluation of the influence of the two initial

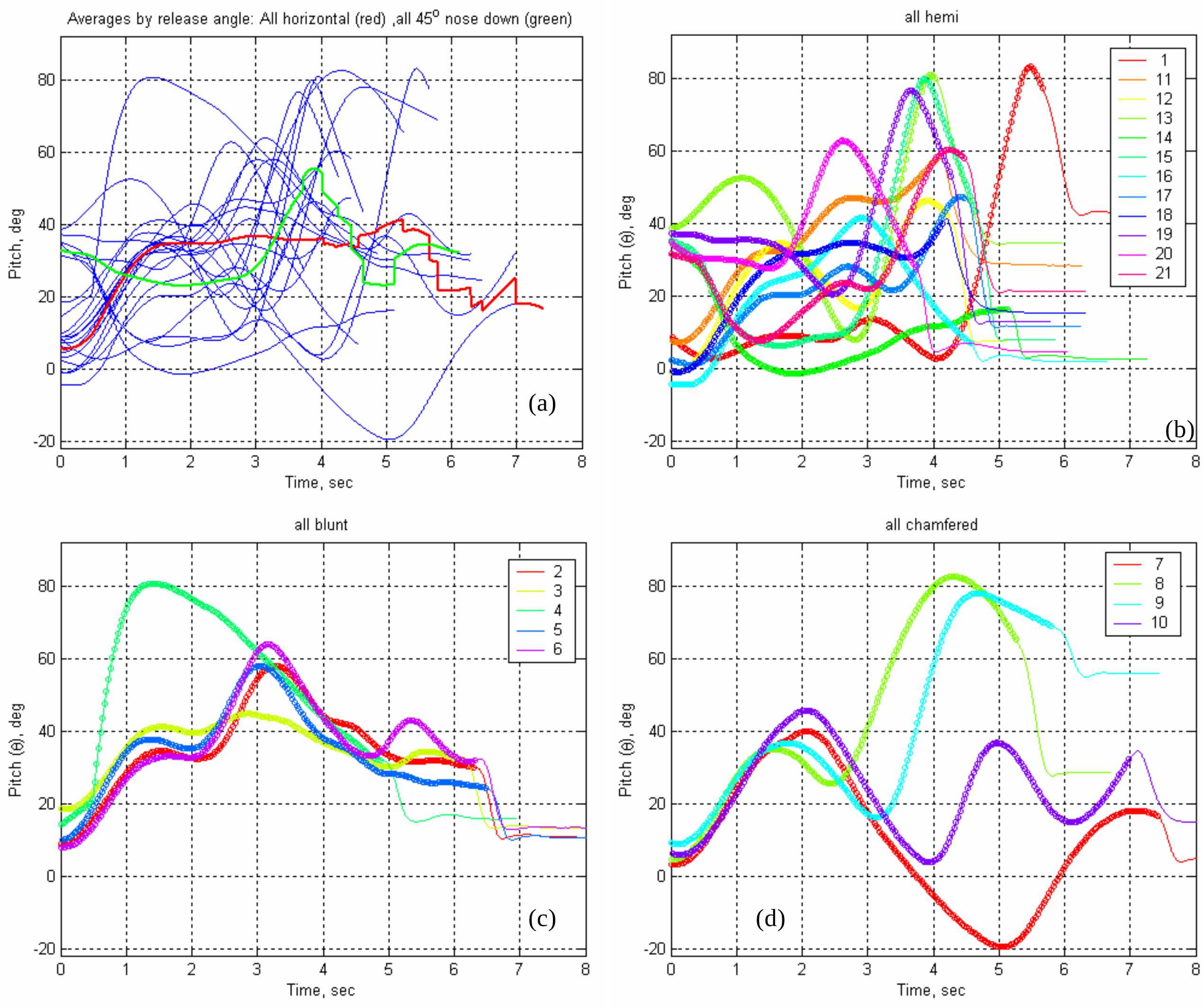

Fig. 8. Pitch versus time for (a) all drops, drops with only (b) hemispherical, (c) blunt, or (d) chamfered noses

orientations on the rest of the trajectory for drops only with the hemispherical nose is given in Fig. 10. The conclusion is largely the same, with any significant differences disappearing after about 1 sec into the drop.

Fig. 11 describes the average and the standard deviation of the lateral velocity, measured in the vertical plane of the cylinder (defined earlier), for all the drops performed (all nose shapes, all release conditions). The negative values of the velocity point to the forward component of the motion, in the direction of the mine's nose. The variability of the standard deviation with time appears to be rather small. The average seems to reach a quasi-constant value, around -1.5 m/s, achieved after approximately 2 seconds into the drop.

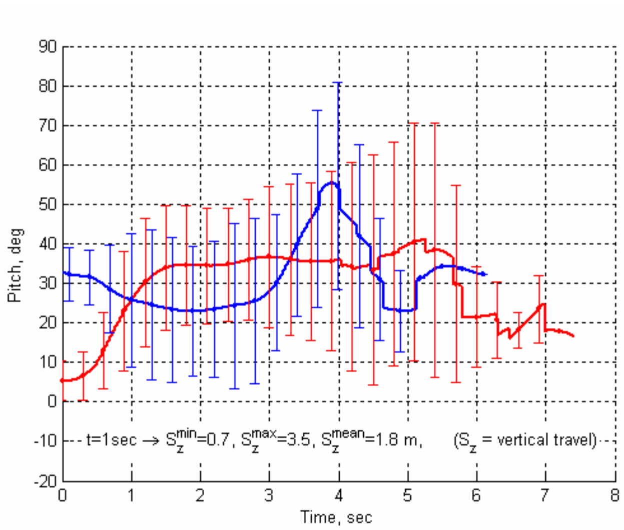

Fig. 9. Average pitch versus time for two release orientations

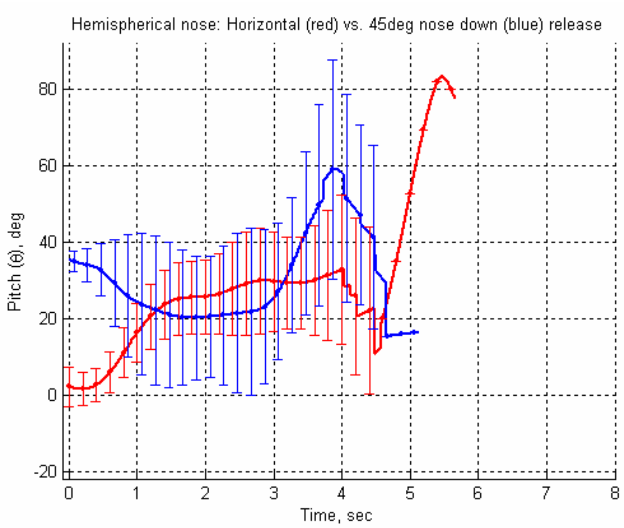

Fig. 10. Average pitch versus time for two release orientations for drops with the hemispherical nose only

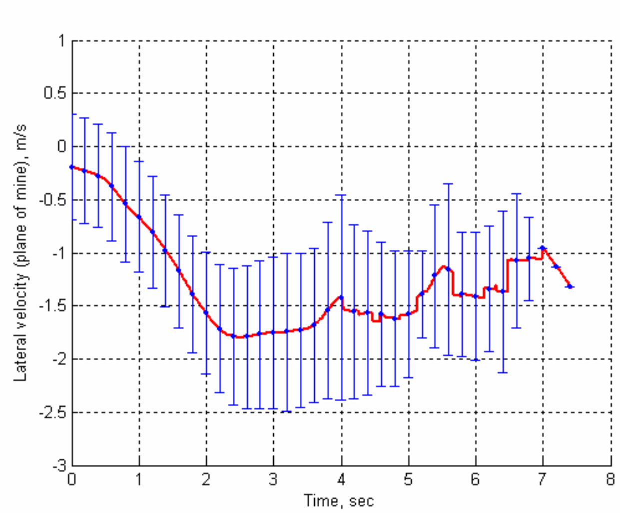

Fig. 11. Average lateral velocity (plane of cylinder) versus time

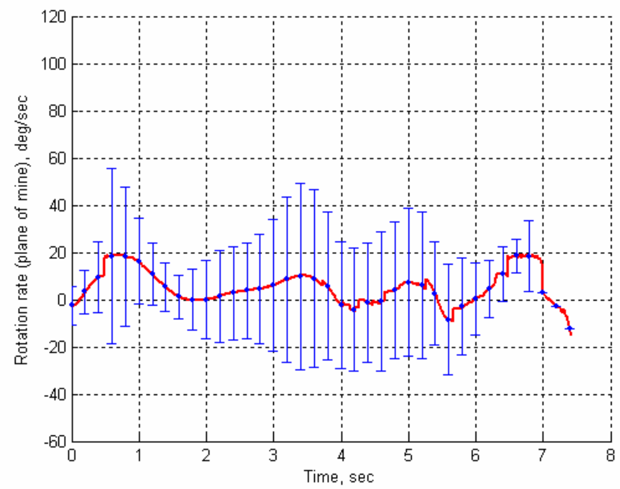

Fig. 12. Average rotation rate (in the plane of the mine) versus time

The variation of the average rotation rate (in the plane of the mine) versus time is presented in Fig. 13. The average appears to be concentrated about zero with equal probability of positive or negative values and the likely bounds extending from about +40 to -40 deg/sec.

Periodicity and extending experimental observations to larger depths

Extensions of the experimental results to depths beyond those actually encountered during the testing was also examined during the data analysis. There are some indications (see Fig. 13, Fig. 14, and Fig. 15) that certain periodicity is present when examining the relationships between some variables.

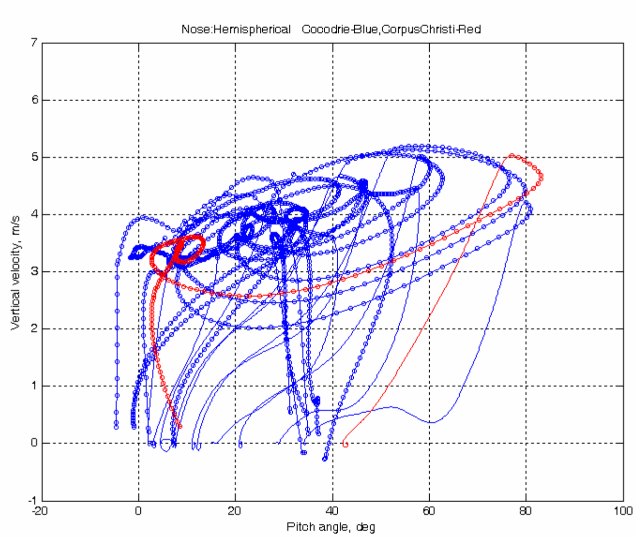

Fig. 13. Vertical component of velocity versus pitch for all drops with the hemispherical nose

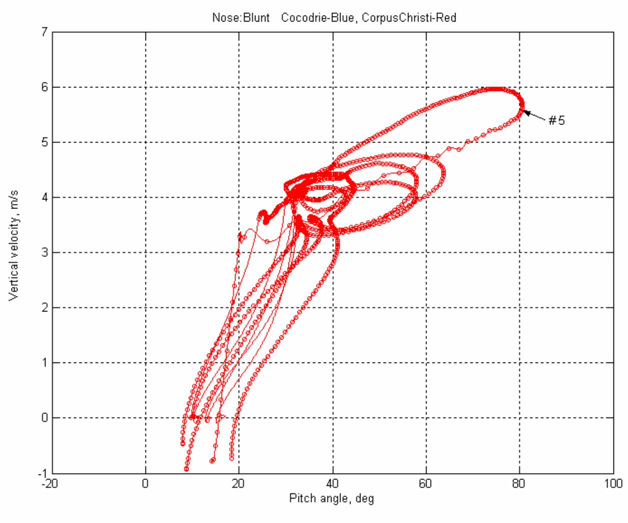

Fig. 14. Vertical component of velocity versus pitch for all drops with the blunt nose

Vertical component of the velocity (V_Z), when plotted versus pitch (?), appears to form "loops" for as long as the mine is free-falling through the water. As described earlier in the text, the lines with the circles, in all three of these figures, represent the trajectory from release and until the first contact with the sediment. Solid lines without the circles represent the continuing motion, or burial into the seafloor. The latter portion of this trajectory is not discussed herein.

It appears that after some period of time, the variation of the V_Z vs. ? reaches a stationary loop when the variables continue to circle until the contact with the seafloor is made. The time (or depth), required to reach this apparent condition, varies depending on the initial orientation, cylinder nose

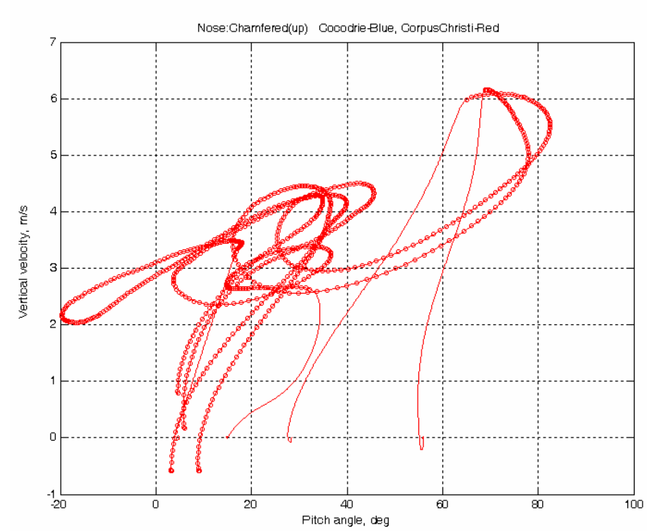

Fig. 15. Vertical component of velocity versus pitch for all drops with the chamfered nose

configuration, or release medium. Fig. 13 presents results for the cylinder with the hemispherical nose, Fig. 14 describes the behavior of the cylinder with the blunt nose, and Fig. 15 – that with the chamfered nose. All three groups appear to possess a certain degree of repeatability, although data are insufficient to make a final judgment.

Some tests, as *e.g.* shown in Fig. 14, do not fit the suggested periodic patterns. Test # 5, labeled in the figure, is the only drop performed from above the water surface with the blunt nose attached. It may be that, due to apparently stabilizing effect of the trailing air bubbles, resulting from the air-water cavity collapse, the depth required to reach the assumed periodic condition is increased. Same effect is not readily noticeable for the hemispherical nose and no air releases with the chamfered nose were performed. One possible explanation of this feature could lie in the fact that the more angular surfaces of the blunt nose configuration, together with the forward biased center of mass, allows for the longer survival of the entrapped air envelope, thus delaying the establishment of the suggested periodic pattern. Similar stabilizing effect of the trailing air bubbles have been observed and characterized in the series of 1/3-scale model mine tests [5].

Additional tests are required to fill the remaining gaps in analyzing the data. Tests at deeper locations, possibly up to 50 or 70 m are necessary to substantiate or disprove the apparently periodic behavior, recorded in these experimental series. At these greater depths, any periodic condition should be attained, regardless of the initial conditions, if the assumptions are correct and no significant disturbances, such as strong horizontal currents highly variable with depth or time, are present.

IV. CONCLUSIONS AND DISCUSSION

An analysis of two series of tests deploying an instrumented cylinder is presented. The discussed results are focused on those parameters that are of primary importance to a currently existing mine burial prediction model. This model is two-dimensional and the discussion is, therefore, concentrated on the behavior and statistical description of the vertical component of velocity, pitch, lateral component of velocity in the plane of the cylinder, and the angular rotation rate in the same plane.

The experiment included a variety of release angles, locations, and nose shapes. The internal instrumentation performed reliably throughout the test series. The modified version of the data processing routine produced good results, reduced number of additional assumptions on the initial state of the instruments, and refined integrating procedures.

Individual analysis of different components of the cylinder motion through the water showed a great degree of random variation. Randomness is present in the trajectories and the distributions of various quantities, such as components of velocity, pitch, and angular rotation rate. This variability affects mine burial prediction, which depends on the accurate knowledge of both impact velocity and orientation. The experimental evidence regarding the individual components of the cylinder motion may be summarized as follows:

1. The vertical velocity appears to reach a steady-state condition, oscillating between 3 and 5 m/s. This condition is reached in about 1.5 seconds after release, corresponding to the depth of approximately 4 m of water. It should be noted that both in-air and in-water releases were performed close to the water surface. Different nose shapes and different release orientation do not appear to influence these average values significantly.
2. A similar conclusion may be reached when observing the variations of the pitch with elapsed time. A great degree of variability is present, indicated by high variance. It appears, however, that the difference in initial orientation vanishes after approximately 1.5 seconds into the free fall. The values of the pitch oscillate, mostly, between 5 and 65 degrees.
3. The average lateral velocity in the plane of the cylinder reaches an approximately stable condition, oscillating around 1.5 m/s with a high standard deviation. There is no noticeable bias present (mean values remain close to zero) in the oscillations of the average rotation rates in the plane of the cylinder with a high degree of variability. Tests at greater depths are required to confirm or disprove whether these values remain constant for the particular cylinder configuration.

Analysis of the influence of a particular nose shape on the behavior of the instrumented cylinders in free-fall leads to the following conclusions. The mean values of the vertical and the horizontal (in the plane of the cylinder) velocities, as well as pitch and pitch rate appear to be unaffected by the nose shape. The distributions of variances of these variables, however, indicate that the cylinders with the chamfered nose produce a more variable trajectory than those with blunt or hemispherical shape. From the mine burial prediction point of view, this implies that penetration of mines with chamfered noses will be more difficult to predict as the values of velocities and orientations at the initial contact with the sediment constitute a wider range, resulting, therefore, in the wider range of calculated burials. The ambiguity of finding a mine buried to a certain depth is therefore higher for this nose shape.

Influence of the initial orientation on the means and variances of the variables analyzed indicates that the knowledge of this condition is important in the mine burial prediction calculations for very shallow depths (less than 4 m). In this range, the values of all the variables have not yet reached their stable or “terminal” conditions (in terms of mean values), characterized by high variance, but are directly affected by the initial release angle, release altitude (if above water), and release media. This implies that reliable mine burial predictions in this depth range may not be possible without the precise knowledge of these release conditions.

Evidence of the stabilizing effect of the trailing air bubble envelope for cylinders released in air appears to confirm the previous findings. Different nose shapes and their different ability to retain the air bubbles seem to influence the timing of attaining the quasi-steady oscillating terminal conditions.

A set of persistent patterns seem to exist in variations of the vertical velocity versus pitch. The motion occurs along ellipsoidal loops, indicating periodic behaviors that differ in detail for the three nose shapes tested. If the suggested periodic patterns do exist, understanding them will increase our ability to define the terminal conditions for the cylinder of certain geometry and mass distribution. Again, accurate prediction may be possible only if accurate information on the initial conditions is also available. If this information is not available, the mine burial prediction model could only utilize the overall range of variations (with equal probability of occurrence) of the various parameters that these loops describe.

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